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Quantifying Potential Measurement Errors and Uncertainties Associated with Bathymetric Change Analysis

by Mark R. Byrnes, Jessica L. Baker, and Feng Li

PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) describes procedures for quantifying error and uncertainty estimates in volume change calculated from comparison of bathymetric surveys from two different times. Initially, this procedure involves an evaluation of the error budget associated with measurement of bathymetry data from individual surveys. Survey accuracy standards are derived from U.S. Army Corps of Engineers (USACE) and National Ocean Service (NOS) hydrographic survey manuals. Next, uncertainties in bathymetric surface characteristics resulting from topographic irregularities and data density are estimated for each surface. Then, root-mean-square (RMS) variations obtained from a comparison of two surfaces are analyzed to estimate total volumetric uncertainties associated with the modeled change surface. Much of the background information regarding survey measurement standards presented in this CHETN may be found in manuals available at: *http://www.thsoa.org/references.htm*.

BACKGROUND: Hydrographic surveys[1] of inlet channels, estuaries, and regional nearshore morphology provide a direct source of data for quantifying temporal changes in bathymetry. Surveys are conducted to determine the configuration of the bottom of water bodies to identify and locate all natural and engineered features that may pose a hazard or concern to navigation. Historically, these data have been collected by USACE and NOS. USACE performs hydrographic and bathymetric surveys that support the planning, engineering design, construction, operation, maintenance, and regulation of navigation, flood control, river engineering, charting, and coastal engineering projects (HQUSACE 2002). NOS conducts hydrographic surveys to document bottom characteristics of harbors, harbor approach channels, inland navigation channels, coastal areas of high commercial use, and offshore regions for nautical chart production (NOS 2000). This CHETN examines the limitations of bathymetry measurements and their significance relative to inherent survey errors and measurement uncertainties associated with data density. Quantification of error and uncertainty estimates for volumetric change calculations gives bounds for reliability of identified erosion and accretion areas, determination of sediment transport pathways, magnitude of sediment transport estimates, and validity of sediment budget estimates.

Historical bathymetry data sets are a primary source of information for assessing large-scale and long-term coastal evolution or site-specific response to natural and human-induced processes. However, the information is rarely used to its fullest extent, possibly due to the amount of analysis necessary to attain an accurate result. Comparison of digital bathymetric data for the same region but different time periods provides a method for calculating net movement of sediment into (accretion) and out of (erosion) a study area. A number of manual and automated techniques have been introduced for

[1] Hydrographic surveys are performed expressly for the purpose of determining depths for navigation and identifying possible obstructions or hazards to navigation. Bathymetric surveys are performed to determine bottom depth not necessarily related to navigation. In this CHETN, the phrases “hydrographic survey” and “bathymetric survey” are interchangeable, as focus is on bottom geomorphic change.

Report Documentation Page					Form Approved OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
SEP 2002	**N/A**	**-**

4. TITLE AND SUBTITLE	
Quantifying Potential Measurement Errors and Uncertainties Associated with Bathymetric Change Analysis (ERDC/CHL CHETN-IV-50)	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Byrnes, Mark R.; Baker, Jessica L.; and Li, Feng**	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **US Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT
This Coastal and Hydraulics Engineering Technical Note (CHETN) describes procedures for quantifying error and uncertainty estimates in volume change calculated from comparison of bathymetric surveys from two different times. Initially, this procedure involves an evaluation of the error budget associated with measurement of bathymetry data from individual surveys. Survey accuracy standards are derived from U.S. Army Corps of Engineers (USACE) and National Ocean Service (NOS) hydrographic survey manuals. Next, uncertainties in bathymetric surface characteristics resulting from topographic irregularities and data density are estimated for each surface. Then, root-mean-square (RMS) variations obtained from a comparison of two surfaces are analyzed to estimate total volumetric uncertainties associated with the modeled change surface.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**17**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

making quantitative estimates of change. Moody (1964) superimposed contour data from charts of different time periods to identify bottom change. Pierce (1969) made data point comparisons for exact geographic positions on charts of different time periods to calculate volumetric changes. Until the 1980s, these two procedures were standard practice (primarily contour overlay) for evaluating historical changes in nearshore bathymetry (e.g., Stauble and Warnke 1974), particularly those related to coastal inlets (Dean and Walton 1973; Olsen 1977). However, in recent years, it has become possible to readily process these data with commercially available surface modeling software to document local and regional sediment transport pathways and quantify long-term net transport rates (Hansen and Knowles 1988; List, Jaffe, and Sallenger 1991; Byrnes and Hiland 1995; Byrnes and Kraus 1999). Because this information is central to understanding geomorphic response to oceanographic processes and coastal zone planning and management practice, data accuracy and potential measurement uncertainties must be assessed for gauging the significance of results.

Hicks and Hume (1997) addressed the issue of data accuracy and measurement uncertainties for bathymetric change on an ebb-tidal delta in New Zealand. Soundings were collected along survey transects 100 m apart to document seafloor morphology. Every other survey line (200 m apart) was used to create two grid surfaces based on triangulation. Volumes for each surface were calculated relative to a constant reference plane (Z = 0) for defined subregions (test blocks) and compared to evaluate uncertainties resulting from data density. Hicks and Hume (1997) documented a mean bed level difference of about 2.4 cm (± 1.2 cm uncertainty) for their entire bathymetry surface and about a 15.3-cm difference (± 7.7 cm uncertainty) over the ebb delta for the 200-m spacing surveys. Assuming that the uncertainty would diminish in proportion to the square root of the number of sampling points, they estimated an overall uncertainty of ± 0.8 cm ($\pm 1.2\,\mathrm{cm}/\sqrt{2}$) for 100-m spacing survey lines. However, it appears that all bed elevation changes, whether positive or negative, were averaged to produce a mean difference in bed elevation that is an underestimate of uncertainty.

BATHYMETRIC SURVEY ACCURACY STANDARDS: The process of obtaining an accurate bathymetric survey is substantially more difficult than that associated with land-based surveying. Measurement error is defined as the difference between a measured value and the true value, and it can be categorized as a blatant error, systematic error, or random error (e.g., Byrnes and Hiland 1994; Kraus and Rosati 1998a; 1998b). Blatant errors (human blunders) can usually be eliminated with adequate quality control procedures. Systematic errors, if identified, are those that can be measured or modeled (estimated) through calibration and removed from the survey data (e.g., tide corrections, instrument calibration). Random errors typically are small errors resulting from the limitation of measuring devices and the inability to perfectly model systematic errors; they can be negative or positive and are governed by the laws of probability. The accuracy of observed bottom elevations for historical and recent surveys is dependent on many random and systematic errors present in the measurement process (Table 1). Unlike land-based surveying, bathymetric and hydrographic surveying has few quality control indicators to check resultant accuracy. Because the bottom elevation being measured is not visible, sometimes even blatant errors are difficult to detect. As such, maintaining prescribed accuracy criteria requires precision, care, and quality control in the measurement process.

Table 1
Hydrographic Survey Positioning Errors (from Umbach 1976)

Horizontal Positioning[1]	Vertical Positioning
Station control • Incorrect geodetic datum • Use of unadjusted or incorrect geodetic positions • Use of survey methods that fail to meet the required accuracy criteria • Use of photogrammetric manuscripts that are incorrect because of bridging errors • Incorrect identification of photo-hydro signals • Incorrect reduction for eccentric placement of electronic control system antennas ashore or afloat • Misidentification of control stations • Excessive use of hydrographic stations to locate other stations in the survey • Incorrectly plotted control	**Tidal and water level observations** • Incorrect predicted or real-time tide or water levels • Improperly accounted time and height shifts in the records • Long periods of missing data • Incorrect zoning • Incorrect datum determination • Incorrect gage, staff, and bench mark elevation relationship • Undetected tide or water level anomalies caused by meteorological conditions
Vessel control - visual • Undetected errors in the instrument, initial or index (i.e., when observing theodolite cuts or sextant angles) • Geometrically weak fixes • Sextant tilt not compensated when using elevated signals • Misidentification of signals • Sextant angle observers not standing close enough to each other or improperly located relative to the antenna and transducer • Poor coordination of the fix event when observing and recording data • Angles or directions read or recorded incorrectly	**Transducer errors** • Incorrectly measured or applied corrections for draft or settlement and squat • Failure to apply the eccentricity of the transducer relative to the fix observation point • Inadequate or erroneous velocity corrections • Unobserved or improperly applied bar check or vertical cast data
Vessel control - electronic • Operation of nonaligned or poorly adjusted positioning systems • Improper use of calibration or field check data • Undetected errors or jumps in distance or lane count • Attenuated or reflected signals over portions of the survey area • Electronic interferences with the positioning system • Failure to correct slant ranges when necessary • Geometrically weak fixes • Use of improper operating frequencies • Failure to reduce the electronic center of the ship to the transducer location	**Depth recorder errors** • Analog systems' phase errors, initial errors, incorrect stylus arm or belt length, incorrect stylus or paper speed, fine arc error, recording paper skew, record misinterpretation (i.e., presence of side echoes, silt or mud bottom, kelp or other marine growth, and strays), improperly accounted wave effects (heave), improperly maintained voltage • Digital systems' incorrect threshold receiving frequency, incorrect calibration (feet or fathoms), scaling errors caused by not allowing for differences between the digital and analog trace, improperly accounted heave.
	Plotting errors • Protractor not in adjustment or improperly used. • Incorrectly set angles on the manual plot • Automated plotter malfunction or improper alignment during the sheet registration • Distortion of the plotting material

[1] Based on 1970 era positioning techniques. Differential GPS has significantly minimized horizontal positioning errors.

Bathymetric and hydrographic surveying involves two primary independent measurements: x-y location (horizontal position), and underwater bottom elevation. The location of a survey vessel is determined by visual (past practice) or electronic (modern practice) methods. However, the elevation of the boat usually is obtained relative to the elevation of the local water surface in making the depth sounding by mechanical or acoustic methods. Therefore, vessel position and elevation are independent measurements with independent accuracies dependent on measurement method, sea state, water temperature and salinity, transducer beam width, bottom sediment type and surface irregularity, and vessel heave-pitch-roll motions. Because there is no method to verify each measured depth (e.g., close-out traverse for land-based surveys), accuracy assessment of an observed

depth can only be determined through statistical estimation. This lack of direct verification makes quantitative comparisons of observed elevations difficult, particularly in areas of irregular terrain. Any effort to compare different surveys made over the same presumed point must consider potential inaccuracies in three dimensions, as well as all the error components contained in the observations that determined the point (HQUSACE 2002). The resultant accuracy of a single depth point is represented by an error ellipsoid as illustrated in Figure 1. The size and orientation of the ellipsoid is determined by the various error components contained in the position and depth measurements. Because it is difficult to independently verify the accuracy of a dynamic hydrographic measurement, the accuracy of a hydrographic survey in most cases is estimated based on repeated equipment calibrations. Another technique used to evaluate the accuracy of individual depths within a hydrographic survey involves comparing measurements for survey lines that intersect. For most recent surveys, cross-check lines are sparse or do not exist at all, but this procedure is recommended.

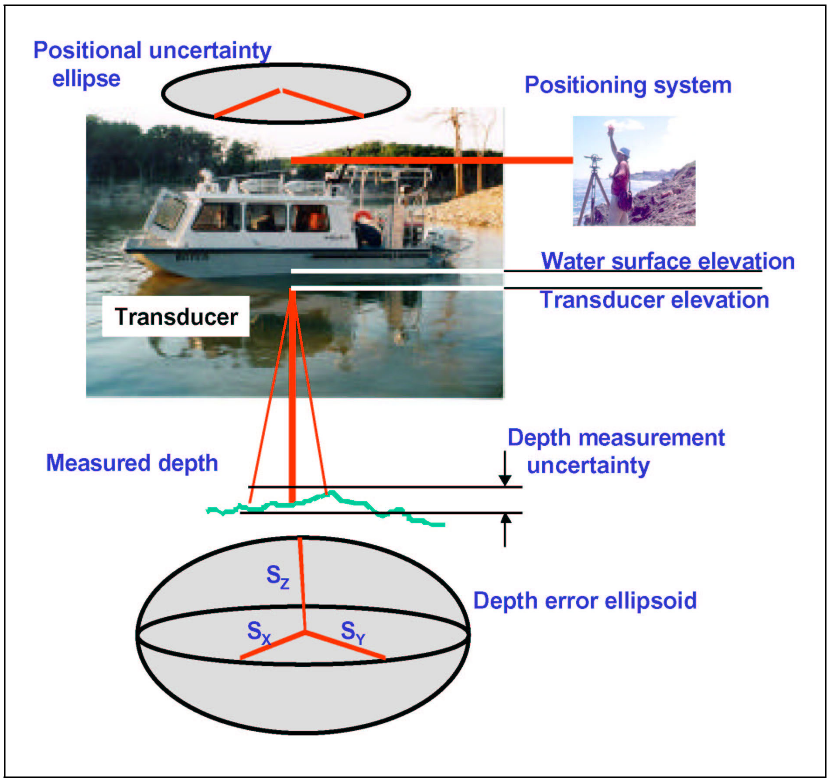


Figure 1. Three-dimensional uncertainty of a measured depth (from HQUSACE 2002)

Recently, the Federal Geographic Data Committee (FGDC) established geospatial positioning accuracy standards for nautical charting hydrographic surveys (FGDC 2000). Four levels of survey accuracy were defined to characterize different accuracy requirements for specific survey areas. Minimum standards designed by the FGDC were established for use by Federal agencies and their contractors (Table 2). USACE and NOS have adopted these minimum standards for hydrographic surveys as a baseline for establishing their own standards. Table 3 illustrates the current technical performance standards for USACE hydrographic surveying.

Table 2
Summary of Minimum Standards for Hydrographic Surveys (from FGDC 2000)

Order	**Special**	**1**	**2**	**3**
Examples of Typical Areas	Harbors, berthing areas, and associated critical channels with minimum underkeel clearances	Harbors, harbor approach channels, recommended tracks and some coastal areas with depths up to 100 m	Areas not described in Special Order and Order 1, or areas up to 200 m water depth	Offshore areas not described in Special Order, and Orders 1 and 2
Horizontal Accuracy (95% Confidence Level)	2 m	5 m + 5% of depth	20 m + 5% of depth	150 m + 5% of depth
Depth Accuracy for Reduced Depths [1] (95% Confidence Level) [2]	a = 0.25 m b = 0.0075	a = 0.50 m b = 0.013	a = 1.0 m b = 0.023	a = 1.0 m b = 0.023
100% Bottom Search [3]	Compulsory	Required in selected areas	May be required in selected areas	Not applicable
System Detection Capability	Cubic features > 1 m	Cubic features > 2 m in depths up to 40 m; 10% of depth beyond 40 m	Cubic features > 2 m in depths up to 40 m; 10% of depth beyond 40 m	Not applicable
Maximum line spacing[4]	100% search compulsory	3 times average depth or 25 m, whichever is greater	3 to 4 times average depth or 200 m, whichever is greater	4 times average depth

[1] To calculate the error limits for depth accuracy, the corresponding values for a and b should be calculated using

$$\text{depth accuracy} \quad \pm \quad \sqrt{a^2 + (b * d)^2}$$

where *a* is a constant depth error (i.e., the sum of all constant errors), *b*d* is the depth dependent error (i.e., sum of all depth dependent errors, where *b* is a factor of depth dependent error and *d* is water depth).

[2] The confidence level percentage is the probability that an error will not exceed the specified maximum value.

[3] A method of exploring the seabed which attempts to provide complete coverage of an area for the purpose of detecting all features addressed in this publication.

[4] The line spacing can be expanded if procedures for ensuring an adequate sounding density are used.

Before determining the RMS error associated with survey depth measurements, a distinction should be made between accuracy and precision associated with observations. Precision is a measure of the closeness of a set of measurements (repeatability) and can be referred to as random error. Accuracy relates to the closeness of measurements to their actual value, which includes random and systematic errors. Figure 2 illustrates the relationship between accuracy and precision relative to the RMS error using examples from actual survey data sets. Although measurements contained on the top plot have high precision, biases due to human error (e.g., incorrect calibrations) result in a relatively large RMS error. Alternately, the bottom plot illustrates lower precision but far less bias in the observations. A degree of randomness in observations is much more acceptable than systematic errors.

The determination of RMS error provides a consistent means of combining biases and random errors for calculating the statistical error associated with depth observations. The equation for calculating the one-dimensional RMS error (Mikhail 1976) is:

$$\text{RMS error} = \sqrt{\left(\sigma^2\right)_{random\ error} + \left(\sigma^2\right)_{bias}} \tag{1}$$

Table 3
Minimum Performance Standards for USACE Hydrographic Surveys (from HQUSACE 2002)

Project Classification		Navigation and Dredging Support Surveys Bottom Material Classification: Hard	Navigation and Dredging Support Surveys Bottom Material Classification: Soft	Other General Surveys and Studies (Recommended Standards)
Resultant Elevation/Depth Accuracy (95%)				
System	**Depth (d)**			
Mechanical	(d < 15 ft)	± 0.25 ft	± 0.25 ft	± 0.25 ft
Acoustic	(d < 15 ft)	± 0.50 ft	± 0.50 ft	± 1.00 ft
Acoustic	(15 < d < 40 ft)	± 1.00 ft	± 1.00 ft	± 2.00 ft
Acoustic	(d > 40 ft)	± 1.00 ft	± 2.00 ft	± 2.00 ft
Object/Shoal Detection Capability				
Minimum object size (95% confidence)		> 0.5 m cube	> 1 m cube	N/A
Minimum # of acoustic hits		> 3	3	N/A
Horizontal Positioning Accuracy (95%)		2 m (6 ft)	2 m (6 ft)	5 m (16 ft)
Planimetric Feature Location Accuracy (95%)		3 m (10 ft)	3 m (10 ft)	3 m (10 ft)
Supplemental Control Accuracy (horizontal and vertical)		3rd order	3rd order	3rd order
Water-Surface Model Accuracy		½ depth accuracy standard	½ depth accuracy standard	½ depth accuracy standard
Minimum Survey Coverage Density		100% Sweep	NTE 60 m (200 ft)	NTE 150 m (500 ft)
Quality Control and Assurance Criteria				
Sound velocity calibration		> 2/day	2/day	1/day
Position calibration check		1/day	1/project	1/project
QA performance test		Mandatory	Required (multibeam)	Optional
Maximum allowable bias		± 0.1 ft	± 0.2 ft	± 0.5 ft

According to the HQUSACE (2002) guidance, calculated RMS error for a single depth measurement or series of measurements should not exceed the stated tolerance listed in Table 3. Minimization of random and systematic errors associated with horizontal and vertical measurements is accomplished by repeated instrument calibration and adherence to standards.

In accordance with FGDC standards, USACE and NOS compute RMS depth errors at the 95 percent confidence interval (1.96-sigma). This means that 95 of 100 depth observations for a given survey will fall within the specified accuracy tolerance. Because the 1-sigma (68 percent) confidence interval is computed when depth accuracy is assessed, it can be converted to the 95 percent RMS confidence level as follows:

$$\text{RMS (95\%) depth accuracy} = 1.96 * \text{RMS (68\%)} \tag{2}$$

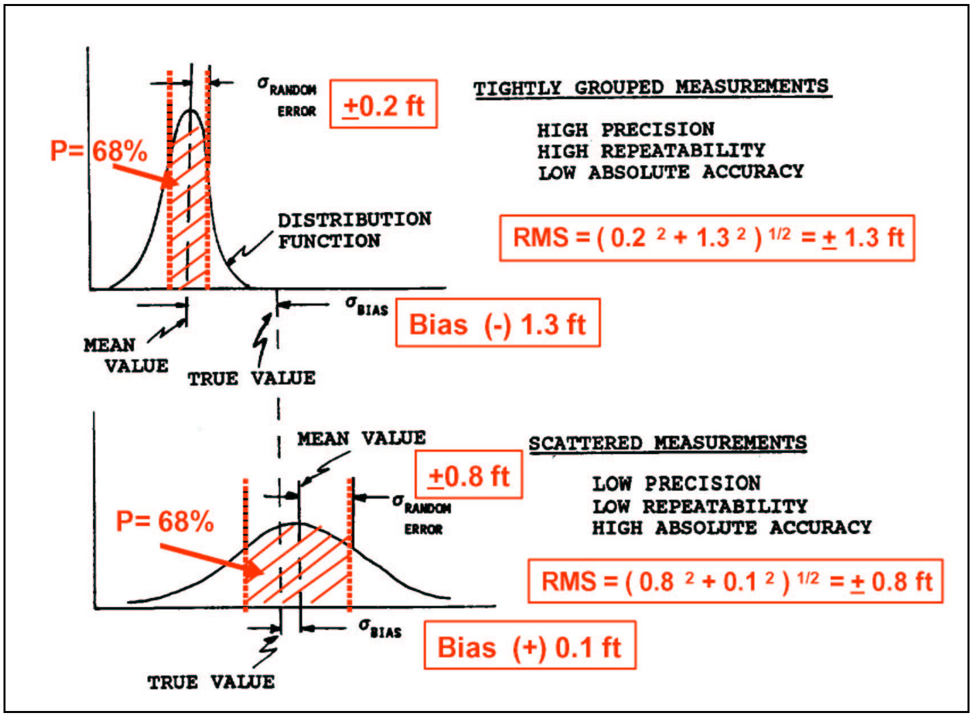


Figure 2. Typical dispersion curves for depth observations (from HQUSACE 2002)

SURVEY ERROR BUDGET: For error sources listed in Table 1, a quantitative estimate of resultant accuracy for a depth measurement (termed error budget) can be determined. HQUSACE (2002) and NOS (2000) estimate the magnitude of error components using acoustic depth measurements based on the type of equipment, the project depth, tidal measurements, and sea state. Table 4 summarizes estimates of depth measurement accuracy for modern survey equipment for USACE projects. These estimates are better than the requirements set forth in Table 2 by FGDC (2000) and the standards established by NOS (2000) for the same potential error sources (± 0.35 to 0.6 m for 10- to 30-m water depths) meet the minimum standards for modern surveys.

Historical surveys, those performed from the late 1800s to the 1950s, were conducted under less stringent standards for data collection relative to the type of positioning and depth measurement equipment available today. In general, however, quality-control requirements for point measurements were detailed, even in the general instructions for hydrographic surveys conducted in the late 1800s (Coast Survey 1878), but the reality of data collection was that equipment limitations and sea state controlled measurement and plotting accuracy. In the 1878 Coast Survey hydrographic manual, accuracy standards for depths recorded in the "smooth water of harbors" were based on soundings made at survey line crossings. For depths < 15 ft, a maximum 0.2-ft depth difference at crossings was allowed.[1] For depths between 72 and 96 ft, a 1.5-ft difference was acceptable. Although limited

[1] American customary units are retained because those were the original units in the 1878 manual. Furthermore, in compiling bathymetric survey data from historical maps, conversion of units is a potential source of error or introduces mistaken accuracy in the number of significant figures that are retained. For example, 1 ft = 0.3048 m, but perhaps the 1-ft measurement was made with an accuracy of 0.1 ft, whereas the strict conversion would imply an accuracy of tenths of millimeters.

Table 4
Quantitative Estimate of Acoustic Depth Measurement Accuracy for Various Project Conditions (from HQUSACE 2002)

Single-beam 200 kHz echo sounder in soft, flat bottom
USCG DGPS vessel positioning accurate to ± 2 m RMS
All values in ± feet

Error Budget Source	**Inland Navigation** Min river slope Staff gage < 0.5 mile 12-ft project < 26-ft boat No H-P-R	**Turning Basin** 2-ft tide range Gage < 1.0 mile 26-ft project < 26-ft boat No H-P-R	**Coastal Entrance** 4-ft tide range Gage < 2.0 mile 43-ft project < 26-ft boat No H-P-R	**Coastal Offshore** 8-ft tide range Gage > 5.0 mile 43-ft project 65-ft boat No H-P-R
Measurement System Accuracy	0.05	0.05	0.10	0.20
Velocity Calibration Accuracy	0.05	0.10	0.10	0.15
Sound Resolution	0.10	0.10	0.10	0.10
Draft/Index Accuracy	0.05	0.10	0.10	0.10
Tide/Stage Correction Accuracy	0.10	0.15	0.25	0.50
Platform Stability Error	0.05	0.20	0.30	0.25
Vessel Velocity Error	0.05	0.10	0.10	0.15
Bottom Reflectivity/Sensitivity	0.05	0.10	0.10	0.15
RMS (95%)	**± 0.37 ft**	**± 0.66 ft**	**± 0.90 ft**	**± 1.32 ft**
Allowed per Table 2	**± 0.50 ft**	**± 1.00 ft**	**± 1.00 ft**	**± 2.00 ft**

specific guidance is provided for irregular bottoms and offshore conditions, it was stated that potential inaccuracies in depth measurements should not exceed a 1 percent difference at crossings for sea conditions. Reference in later versions of this manual (Hawley 1931; Adams 1942; Umbach 1976) to allowable differences at survey trackline crossings was used to define depth accuracy limits. For surveys conducted in the early- to mid-1900s, when positioning and depth measurement techniques were advancing from manual to electronic, depth differences at offshore line crossings were not to exceed ± 2 ft. For late-1900s surveys, Umbach (1976) stated that in areas of smooth bottom with depths less than 60 ft, depth differences at crossings should not exceed 1 to 2 ft. In areas with irregular surface features and water depths greater than 60 ft, measurement differences were not to exceed 3 percent of the water depth.

Although the determination of RMS (95 percent) error is more rigorous for modern surveys, reasonable estimates for historical observations based on the previous information suggests that potential errors in water depth measurements for late 1800s and early 1900s surveys were approximately ± 3 to 4 ft. For mid-1900s hydrographic surveys, RMS (95 percent) measurement errors were about ± 2 to 3 ft. Based on present USACE and NOS standards, modern horizontal positioning and vertical measurement equipment have decreased potential inaccuracies to about ± 0.5 to 1 ft for surveys conducted in less than 100-ft water depth.

TERRAIN IRREGULARITIES AND SURFACE UNCERTAINTIES: To this point, most discussion has focused on systematic and random measurement error, as opposed to data density considerations. The density of bathymetry data compiled to describe the seafloor, the magnitude and frequency of terrain irregularities, and survey trackline orientation relative to bathymetric features

are the most important factors influencing uncertainties in volume change calculations between two bathymetric surfaces (HQUSACE 2002). As an example, most surveys describing seafloor conditions at a specific time are conducted along lines a defined distance apart. Line spacing may vary in response to seafloor irregularities, but most surveys do not have 100 percent coverage across the entire surface, and interpolation between points is necessary to describe the surface. Interpolation between survey points or lines of points provides an estimate of the variations in depth that exist when describing seafloor shape with these data sets. Uncertainties can be quantified by comparing variations in depth between adjacent survey lines at defined locations on the bathymetric surface. If depth variations between survey lines are large (few data points describing variable bathymetry), uncertainty will be large. Calculating average elevation differences between survey lines provides the best estimate of uncertainty for gauging the significance of volume change estimates between two surfaces.

It is important to quantify limitations in survey measurements and document potential systematic errors that can be eliminated during quality control procedures. However, most measurement errors associated with present and past surveys are considered random over large areas. As such, random errors cancel relative to change calculations derived from two surfaces. This is not the case when systematic errors, defined at survey line crossings, are identified for specific surfaces. If identified, these errors must be incorporated with uncertainties resulting from terrain irregularities and data density.

BATHYMETRIC SURFACE COMPARISON: Comparative analysis of bathymetry data for different time periods is used to document changes in channel cross section, calculate dredged sediment volumes, quantify long-term net sediment transport rates, and determine regional sediment budgets (Byrnes and Hiland 1995; Rosati and Kraus 1999, 2001). Two common representations of bathymetric surfaces from hydrographic data are Triangulated Irregular Networks (TIN) and grids. Creation of a TIN surface is best suited where data are sparse or unevenly distributed throughout the survey area. Furthermore, all measured data points are used and honored directly, as they form the vertices of triangles that comprise the modeled terrain (Milne 1991). For multibeam data, where coverage is continuous, gridding provides a good representation of surface characteristics; however, a TIN surface would represent bathymetric features equally as well. Therefore, it is recommended that the TIN method be used for creating accurate model surfaces from hydrographic data for calculating volume change and documenting sediment transport patterns.

Figure 3 presents an example of two bathymetric surfaces created using the TIN method. Prior to surface modeling, both data sets were transformed to a common horizontal and vertical datum. The combined 1977/78 surface was created using fewer points than the 2000 data set; however, shoal characteristics offshore Ocean City Inlet, MD, are well represented for both time periods. Visual verification of surface character is a critical quality control procedure because terrain irregularity caused by differences in data density is the major factor controlling the accuracy of volume change computations (HQUSACE 2002), particularly in areas with irregular bathymetry. General morphologic characteristics are similar for both surfaces; however, there are some significant differences between the two time periods. The ebb shoal appears to have expanded to the south-southwest, and shallow deposits seaward of Assateague Island appear to be supplying significant

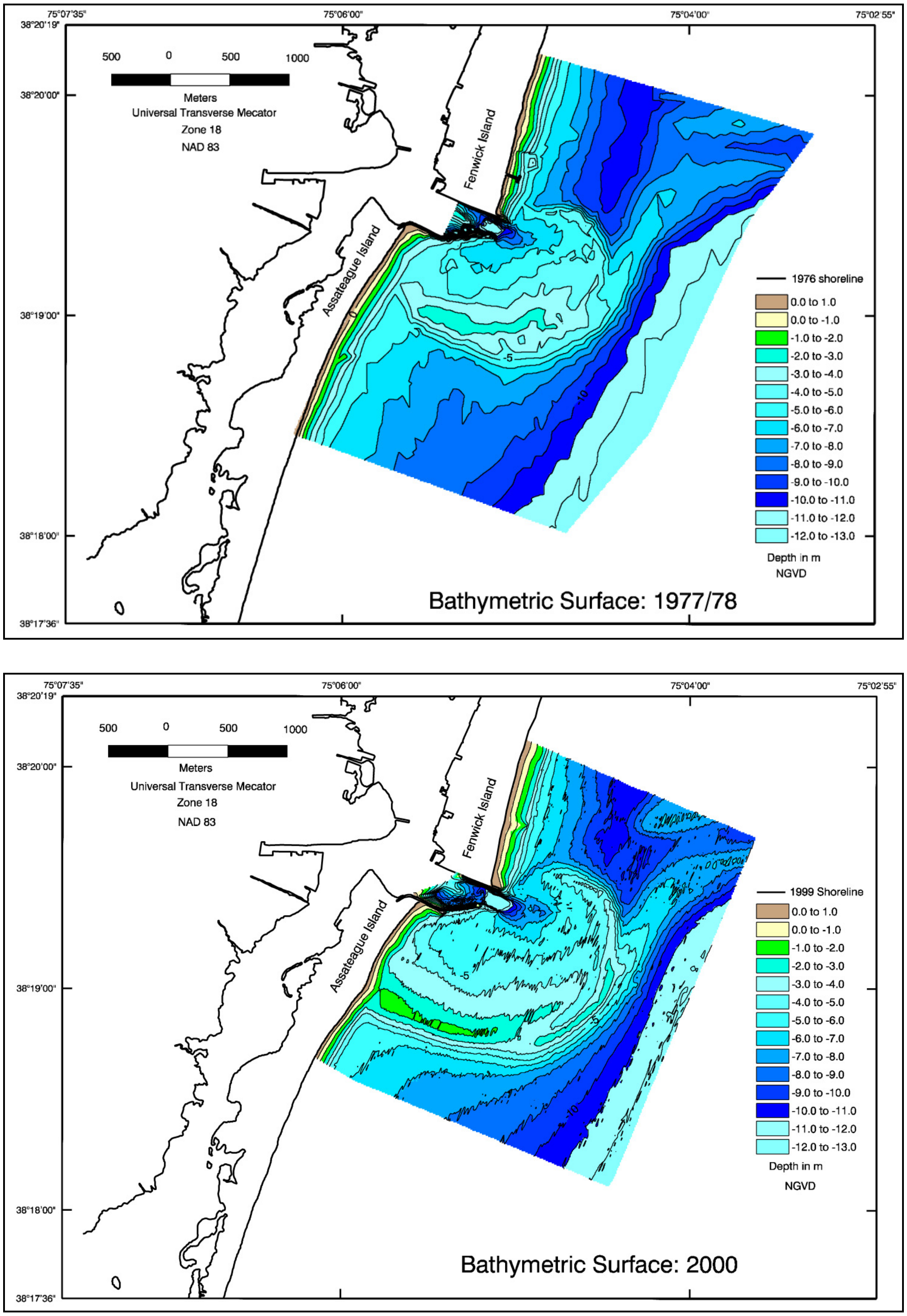


Figure 3. Bathymetric surface at Ocean City Inlet, MD, for the periods 1977/78 (NOS data) and 2000 (HQUSACE data)

quantities of sand to the beach. Quantifying these and other visual trends is valuable coastal engineering information for channel navigation and beach response studies. Digital comparison of these surfaces documents volume changes within measurement and analysis uncertainties.

QUANTIFYING UNCERTAINTY ESTIMATES: Calculation of change in sediment volume from bathymetry data sets have been made for years to determine dredged quantities from channels and borrow sites, and coastal sediment transport rates. Although guidance has existed from the earliest surveys to present regarding accuracy of water depth observations, estimates of uncertainty relative to computed change typically are not provided. HQUSACE (2002) describes the three primary factors that impact the accuracy of dredged volume computations: terrain irregularity and data density; depth measurement bias errors; and deviations in depth observations. Although the three factors must be considered in estimating uncertainty, terrain irregularity and data density have the greatest influence on overall accuracy of volume change or dredged quantity estimates (HQUSACE 2002).

An estimate of volume uncertainties relative to terrain irregularities and data density can be determined by comparing surface characteristics at adjacent survey lines. In general, the closer the line spacing (increased data density), the lower the uncertainty. In addition, for surfaces where terrain irregularities are small, estimated volume uncertainties will be lower than areas with the same line spacing and greater bathymetric variations. To quantify potential uncertainties in elevation between survey lines, one can determine the cross-sectional area associated with survey lines of equal length. The absolute change in cross-sectional area between adjacent survey lines, divided by survey line length, provides an estimate of the potential uncertainty (± ½ the average elevation difference between lines) associated with interpolating between lines for a specific bathymetric surface. If topographic variations are large between lines, the uncertainty will be large relative to volume change between two surfaces for the same geographic area. Estimated uncertainties must be determined for each bathymetry data set so combined uncertainty for the volume change surface is computed properly.

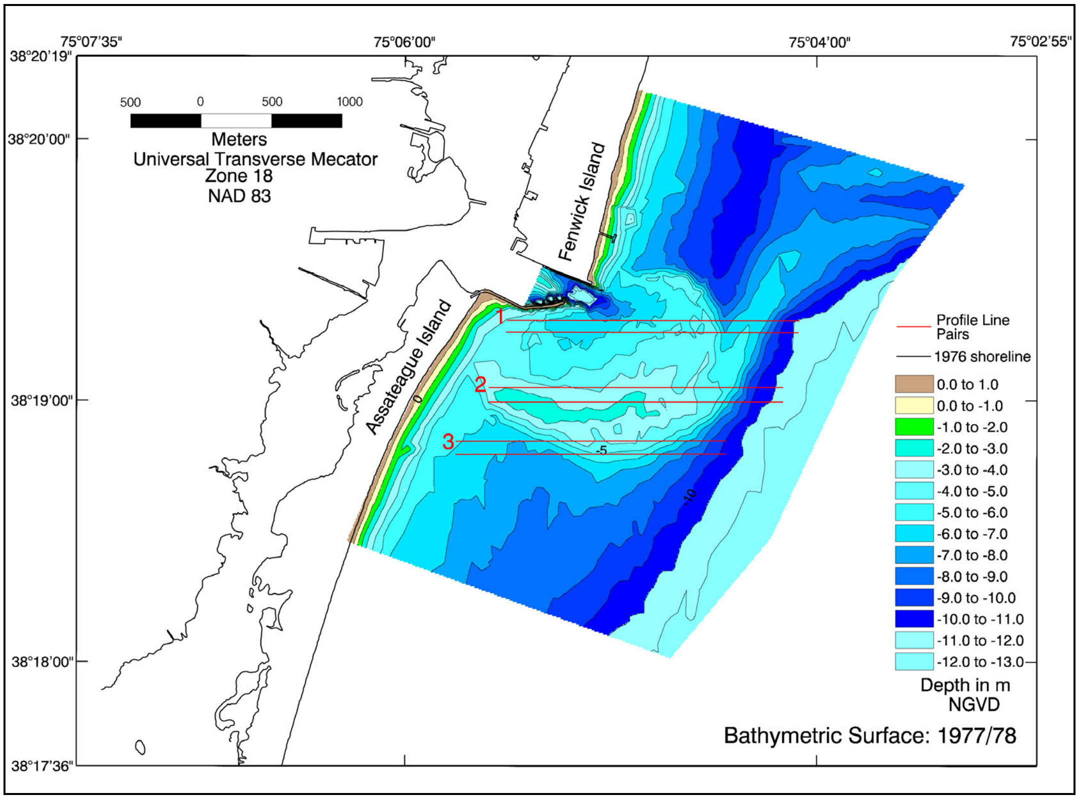
Although bias errors in depth measurements exist in all survey data sets, the magnitude of bias error generally is insignificant in modern surveys (1950s to present). A constant depth bias can be estimated from cross-line checks or multibeam performance test data (HQUSACE 2002). Modern bathymetry surveys contain minimal depth biases as required by survey instruction manuals (NOS 2000; HQUSACE 2002). The standard deviation of depth measurements from cross-line data is used to estimate errors for individual survey points. For a full-coverage survey (10 to 15 points per second), data points would contain no error due to inaccuracies in individual depths (i.e., error is randomly distributed over a full-coverage data set; HQUSACE 2002). In comparing bathymetry surveys from two time periods for the same survey area, deviations in depth observations also cancel, assuming water, sediment, and surface characteristics are similar for each time period. As such, terrain irregularity and data density are the primary limiting factors on accuracy of volume change computations, provided that systematic biases have been eliminated.

As an example, the 1977/78 and 2000 bathymetric surfaces for Ocean City Inlet, MD, were evaluated for potential measurement errors prior to computing volume changes. Error analysis was based on the information presented in NOS (2000) and HQUSACE (2002). For both data sets, a minimal number of survey line crossings were available for evaluating survey bias or the standard

deviation of depth measurements at line crossings. As such, guidance provided in NOS (1976) and HQUSACE (2002) survey manuals was used to estimate these sources of error. Based on survey manual instructions, it was concluded that bias errors were significantly minimized (effectively zero) as part of survey quality control procedures, so volume changes computed over a given area for a large number of observed data points would have no error due to measurement inaccuracies for individual depths. This means that inherent uncertainties associated with the 1977/78 and 2000 surfaces are a function of topographic irregularities relative to the density of survey lines (i.e., uncertainties encountered caused by interpolation between survey lines).

Depth uncertainties associated with interpolation between survey lines for the 1977/78 and 2000 bathymetric surfaces can be evaluated by comparing cross-sectional areas associated with adjacent survey lines for areas representing common geomorphic features across each bathymetric surface. The difference in cross-sectional area between adjacent survey lines of equal length represents variability that is distributed evenly between the lines to estimate shape of the bathymetric surface. This variation in bed elevation (and cross-sectional area) reflects the range in surface uncertainty that may be encountered when interpolating between lines. After summing the absolute value of the difference in cross-sectional area between adjacent lines, the value is divided by the length of the survey lines to obtain an estimate of average surface elevation uncertainty (± ½ the value) resulting from terrain irregularities between survey lines. A number of adjacent lines (if not all line pairs) for the area over which volume change comparisons are to be made should be evaluated to document potential mean bed elevation differences.

To determine the average elevation uncertainties associated with the 1977/78 and 2000 bathymetric surfaces at Ocean City Inlet, MD, multiple sets of adjacent survey lines were analyzed for variations in depth across each bathymetric surface. Lines were chosen that represented bathymetric variations within areas selected for quantifying changes in seafloor topography. Figure 4 illustrates line pairs used to document topographic uncertainty related to prominent geomorphic features (e.g., shoals, channel, gently-sloping shelf surface) and data density. Each set of line pairs overlays bathymetry survey lines so the measured depth values are used to quantify uncertainty between and along lines. After identifying survey line locations of equal length, the next step is to calculate the absolute value of the difference in cross-sectional area between transect pairs. For example, the center line pair for the 2000 surface (labeled 2) illustrates a difference in cross-sectional area of 185 m^2 over a distance of 1,783 m. With this information, one can calculate the average elevation difference between these two survey lines by dividing one half of the absolute cross-sectional area difference by the line distance. This process can be completed for any combination of adjacent line pairs (at least three for areas the size of the Ocean City Inlet data set) for modern and historical bathymetry data sets. After completing an analysis of elevation differences for selected surface line pairs, average elevation difference for the entire surface is computed by summing individual elevation differences and dividing by the number of line pairs. As such, each bathymetric surface is associated with an average elevation difference. For the 1977/78 ebb-shoal surface at Ocean City Inlet, estimated average elevation uncertainty was determined to be ±0.38 m based on three line pairs shown in Figure 4. For the 2000 surface, estimated elevation uncertainty was ±0.11 m. Combining this information to gauge the impact of potential uncertainties associated with terrain irregularities and data density resulted in an RMS variation of ± 0.4 m.



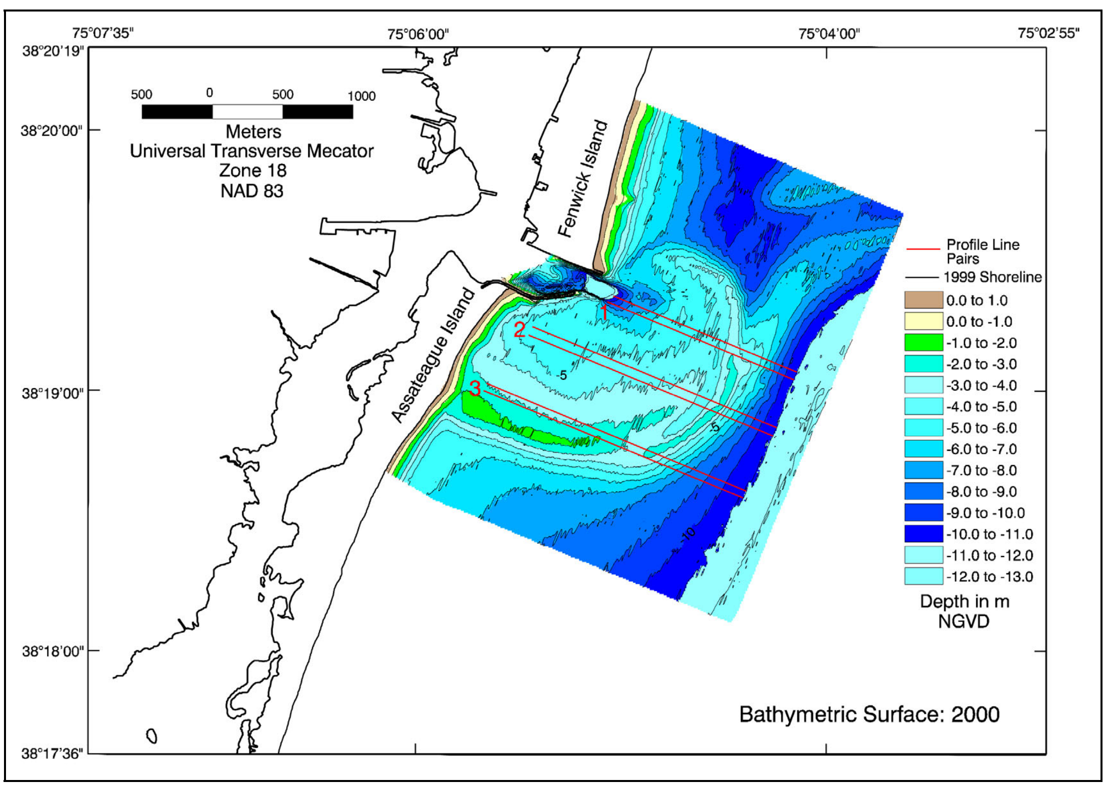


Figure 4. Location of three adjacent survey line pairs for documenting elevation uncertainty for the 1977/78 and 2000 bathymetric surfaces

Hicks and Hume (1997) evaluated uncertainty between survey lines by creating two interpolated grid surfaces based on triangulation with every other survey transect. Volumes for each surface were calculated relative to a constant reference plane (Z= 0) for defined subregions (test blocks) and compared. Their results indicated a mean bed level uncertainty of ± 0.8 cm, an order of magnitude less than elevation uncertainty determined for the 2000 Ocean City Inlet surface. As a result of this difference in uncertainty, the 2000 bathymetric surface for offshore Ocean City Inlet (60-m line spacing) was analyzed using the same technique as Hicks and Hume to document mean bed elevation differences resulting from interpolation between survey lines. However, when calculating the mean difference in bed elevation between the interpolated surface and the survey data, we used the absolute value of change so the magnitude of elevation uncertainty was represented properly. Mean bed level difference over the entire surface was 0.21 m (± 0.10 m) for a 120-m survey line spacing. Assuming that bed elevation uncertainty would diminish in proportion to the square root of the number of sampling point (as per Hicks and Hume), mean elevation uncertainty would decrease to ± 7 cm for a 60-m line spacing. The average elevation uncertainty determined in the previous paragraph based on three representative survey line pairs was ± 11 cm. If the mean elevation difference resulting from interpolation between survey lines was determined by averaging positive and negative elevation differences (as opposed to the absolute value of differences), the mean elevation uncertainty would decrease to about ± 6 mm, a number similar to that determined by Hicks and Hume (1997) for a survey of an ebb-tidal delta in New Zealand (± 8 mm). Because we are interested in evaluating the average magnitude of change resulting from interpolation between survey lines, averaging positive and negative elevation differences significantly underestimates elevation uncertainty.

VOLUME CHANGE: Figure 5 illustrates areas of accretion and erosion for the shelf surface seaward of Ocean City Inlet for the period 1977/78 and 2000. An arc of sediment accretion is associated with ebb shoal growth and migration to the south-southwest of the inlet. Deposition on the ebb shoal and at the shoreline along northern Assateague Island appears significant. Based on the ± 0.4-m uncertainty estimate previously presented, one can determine estimated volume uncertainty for comparison with change measurements knowing the volume of erosion or accretion occurring between the 0 and ± 0.4-m volume change contour.

Knowing the elevation uncertainty estimate for the 1977/78 to 2000 volume change surface for Ocean City Inlet, estimate the volume uncertainty associated with calculated sediment deposition on the ebb shoal, bypassing bar, and attachment bar illustrated on Figure 5. Total deposition in the ebb-shoal polygon is 518,900 m^3 over a surface area of 310,800 m^2. Deposition above the 0.4-m contour for this same area totaled 414,500 m^3. For the bypassing bar polygon, net deposition is 3,337,200 m^3, and deposition above the 0.4-m deposition contour is 2,756,200 m^3; surface area is constant at 1,452,500 m^2. For the attachment bar, net deposition is 446,600 m^3, and deposition above 0.4 m is 341,300 m^3.

Table 5 illustrates volume change results and associated uncertainty estimates for the ebb shoal at Ocean City Inlet. If one were more interested in calculating volume change on the shoreface adjacent to the ebb shoal, uncertainty should be quantified based on survey lines from that region. Once calculated, volume uncertainty estimates provide a reasonable limit to gauge the significance of volume change determined from bathymetric surveys for documenting dredging quantities and

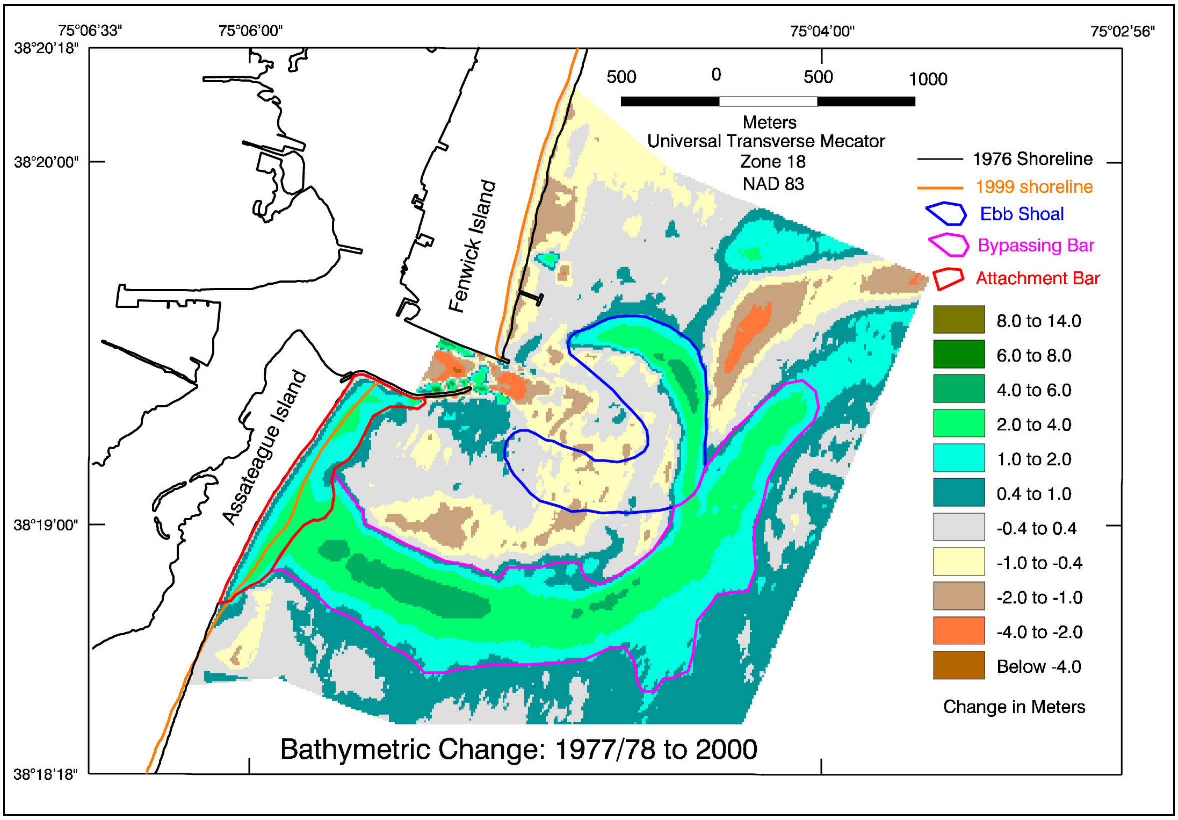


Figure 5. Bathymetric change at and adjacent to Ocean City Inlet, MD

Table 5
Volume Change and Estimated Uncertainty at Three Depositional Zones on Ebb-Tidal Delta at Ocean City Inlet, MD

1977/78 to 2000	Total (m^3)	Above 0.4 (m^3)	Estimated Uncertainty (m^3)
Ebb Shoal	518,900	414,500	**±104,400**
Bypassing Bar	3,337,200	2,756,200	**±581,000**
Attachment Bar	446,600	341,300	**±105,300**

regional sediment transport rates associated with coastal science and engineering projects. Without this analysis, the confidence level associated with volume change data cannot be determined objectively, and data reliability is open-ended.

ADDITIONAL INFORMATION: This CHETN was produced under the Coastal Inlets Research Program (CIRP) Work Unit "Inlet Channels and Adjacent Shorelines" by Dr. Mark R. Byrnes, Ms. Feng Li, and Ms. Jessica L. Baker, Applied Coastal Research and Engineering. Ms. Julie D. Rosati at the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, is the work unit Principal Investigator. Questions can be addressed to Dr. Byrnes at *mbyrnes@appliedcoastal.com* or to Ms. Rosati at *Julie.D.Rosati@erdc.usace.army.mil*. For information about CIRP, please consult the Web site *http://cirp.wes.army.mil/cirp/cirp.html* or contact the CIRP Program Manager, Dr. Nicholas C. Kraus at

Nicholas.C.Kraus@erdc.usace.army.mil or by telephone at (601) 634-2016. This CHETN should be cited as follows:

> Byrnes, M. R., Baker, J. L., and Li, Feng (2002). "Quantifying potential measurement errors associated with bathymetric change analysis," ERDC/CHL CHETN-IV-50, U.S. Army Engineer Research and Development Center, Vicksburg, MS. (*http://chl.wes.army.mil/library/publications/chetn*).

REFERENCES

Adams, K.T. (1942). *Hydrographic manual (Edition 2)*. U.S. Department of Commerce, U.S. Coast and Geodetic Survey, U.S. Government Printing Office, Washington, DC, 940 pp. (*http://www.thsoa.org/pdf/hm1942/hm143c.pdf*)

Byrnes, M.R., and Hiland, M.W. (1994). "Compilation and analysis of shoreline and bathymetry data (Appendix B)," N.C. Kraus, L.T. Gorman, and J. Pope, ed., "Kings Bay Coastal and Estuarine Monitoring and Evaluation Program: Coastal Studies," Technical Report CERC-94-09, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Byrnes, M.R., and Hiland, M.W. (1995). "Large-scale sediment transport patterns on the continental shelf and influence on shoreline response: St. Andrew Sound, Georgia to Nassau Sound, Florida, U.S.A," *Large-scale coastal behavior.* J.H. List and J.H.J. Terwindt, ed., Marine Geology 126, 19-43.

Byrnes, M.R., and Kraus, N.C. (1999). "Regional sediment transport patterns adjacent to Canaveral Harbor, Florida." *Proceedings Coastal Sediments '99*. N.C. Kraus and W.G. McDougal, ed., American Society of Civil Engineers, New York, 750-760.

Coast Survey. (1878). *General instructions, hydrographic surveys division*. U.S. Government Printing Office, Washington, DC, 53 pp. (*http://www.thsoa.org/pdf/hm1878/1878all.pdf*)

Dean, R.G., and Walton, T.L. (1973). "Sediment transport processes in the vicinity of inlets with special reference to sand trapping," Proceeding of the International Estuarine Research Federation Conference. L.E. Cronin, ed., Academic Press, New York, 129-149.

FGDC. (2000). "Geospatial positioning accuracy standards, part 5: Standards for nautical charting hydrographic surveys," Draft Report, Federal Geographic Data Committee, Reston, VA, 11 pp. (*http://www.thsoa.org/pdf/part5.pdf*)

Hansen, M., and Knowles, S. C. (1988). "Ebb-tidal delta response to jetty construction at three South Carolina inlets." *Hydrodynamics and sediment dynamics of tidal inlets*. D.G. Aubrey and L. Weishar, ed., Springer-Verlag, New York, 364-381.

Hawley, J.H. (1931). *Hydrographic manual* (Edition 1). U.S. Department of Commerce, U.S. Coast and Geodetic Survey, U.S. Government Printing Office, Washington, DC, 191 pp. (*http://www.thsoa.org/pdf/hm1931/hm1931.pdf*)

Headquarters, U.S. Army Corps of Engineers. (2002). "Hydrographic surveying," Draft Engineer Manual EM 1110-2-1003, U.S Army Corps of Engineers, Washington, DC, 506 pp. (*http://www.usace.army.mil/inet/usace-docs/eng-manuals/em1110-2-1003/toc.htm*)

Hicks, D.M., and Hume, T.M. (1997). "Determining sand volumes and bathymetric change on an ebb-tidal delta," *Journal of Coastal Research* 13(2), 407-416.

Kraus, N.C., and Rosati, J.D. (1998a). "Estimation of uncertainty in coastal-sediment budgets at inlets," Coastal Engineering Technical Note CETN-IV-16, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Kraus, N.C., and Rosati, J.D. (1998b). "Interpretation of shoreline-position data for coastal engineering analysis," Coastal Engineering Technical Note CETN-II-39, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

List, J. H., Jaffe, B. E., and Sallenger, A. H. (1991). "Large-scale coastal evolution of Louisiana's barrier islands." *Proceedings Coastal Sediments '91*. N. C. Kraus, K. J. Gingerich, and D. L. Kriebel, ed., ASCE, New York, 1532-1546.

Mikhail, E. M. (1976). *Observations and least squares*. Dun-Donnelley Publishing, New York, 497 pp.

Milne, P. H. (1991). "Survey software for digital terrain modeling," *Terrain modelling in surveying and civil engineering*. G. Petrie and T. J. M Kennie, ed., McGraw-Hill, New York, 171-185.

Moody, D. W. (1964). "Coastal morphology and processes in relation to the development of submarine sand ridges off Bethany Beach, Delaware," Ph.D diss., Johns Hopkins University, Baltimore, MD, 167 pp.

NOS. (2000). "NOS hydrographic surveys specifications and deliverables," U.S. Department of Commerce, Silver Spring, MD, 128 pp. (*http://chartmaker.ncd.noaa.gov/hsd/specs/specs.htm*)

Olsen, E. J. (1977). "A study of the effects of inlet stabilization at St. Marys Entrance, Florida." *Proceedings Coastal Sediments '77*. ASCE, New York, 311-329.

Pierce, J. W. (1969). "Sediment budget along a barrier island chain," *Sedimentary Geology* 3, 5-16.

Rosati, J. D., and Kraus, N. C. (1999). "Formulation of sediment budgets at inlets." Coastal and Hydraulics Engineering Technical Note CHETN-IV-15 (Revised August 1999), U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Rosati, J. D., and Kraus, N. C. (2001). "Sediment budget analysis system (SBAS): Upgrade for regional applications," Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN-XIV-3, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Stauble, D. K., and Warnke, D. A. (1974). "The bathymetry and sedimentation of Cape San Blas shoals and shelf off St. Joseph Spit, Florida," Journal of Sedimentary Petrology 44(4); 1037-1051.

Umbach, M. J. (1976). "Hydrographic manual: Fourth edition," U.S. Department of Commerce, Rockville, MD, 400 pp. (*http://www.thsoa.org/pdf/hm1976/hmall.pdf*)